

# Higgs pair production and the Higgs potential

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# What is a Higgs, and why do we expect it?

Obs'vn #1: approx.  $SU(2)_L$  symmetry: broken!  
( $M_{W,Z}$  breaks gauge invariance)

Obs'vn #2:  $WW \rightarrow WW$  violates unitarity at high energy, unless scalar or strong dynamics appears

Weak coupling theory approach:

- write a minimal Higgs sector:  
1  $SU(2)_L$  complex scalar doublet

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} w_1 - iw_2 \\ \phi - iz \end{pmatrix}$$

breaking yields 1 neutral physical state  $\textcolor{red}{h}$   
w/ custodial  $SU(2)$  symmetry &  $m_\gamma \equiv 0$

- $\Phi$  must also generate fermion masses  
(from  $ff \rightarrow WW$  scattering unitarity)

$$Y_u \begin{pmatrix} u_L \\ d_L \end{pmatrix} \Phi u_R \quad m_u = \frac{|Y_u|v}{\sqrt{2}}$$

$$Y_d \begin{pmatrix} u_L \\ d_L \end{pmatrix} \Phi^\dagger d_R \quad m_d = \frac{|Y_d|v}{\sqrt{2}}$$

$$Y_\ell \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix} \Phi^\dagger \ell_R \quad m_\ell = \frac{|Y_\ell|v}{\sqrt{2}}$$

# The $SU(2)_L$ Higgs Lagrangian

$$\mathcal{L}_H = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$$

( $D_\mu = \delta_\mu + ig' \frac{Y}{2} B_\mu + ig \frac{\sigma^i}{2} W_\mu^i$  “minimal coupling”)

simple potential:

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$\mu^2 \rightarrow < 0$  breaks symmetry spontaneously

“Higgs Theorem”:

$w_1, w_2, z \rightarrow W_L^+, W_L^-, Z_L$  (now massive)

$m_\gamma = 0$  exactly!

$\phi$  becomes massive physical scalar

Lots of mysteries:

- why is  $v \neq M_{Pl}$ ? or  $\Lambda_{QCD}$ ?
- 18 bizarre Yukawa couplings, and  $Y_t \approx 1$

...but right now we don't care *why..*

## The SM Higgs potential

Higgs potential minimizes at

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix} \text{ and } v = \sqrt{-\mu^2/|\lambda|}$$

note that  $\lambda$  fixed by unitarity:

$$\lambda_{SM} = M_h^2 / 2v^2$$

for 3,4-point self-couplings  $-6v\lambda, -6\lambda$   
( $ZZ \rightarrow HH, WW \rightarrow HHH$  scattering)

Pheno: measure coeff's of effective potential

$$V(\eta_H) = \frac{1}{2} M_h^2 \eta_h^2 + \lambda v \eta_h^3 + \frac{1}{4} \tilde{\lambda} \eta_h^4$$

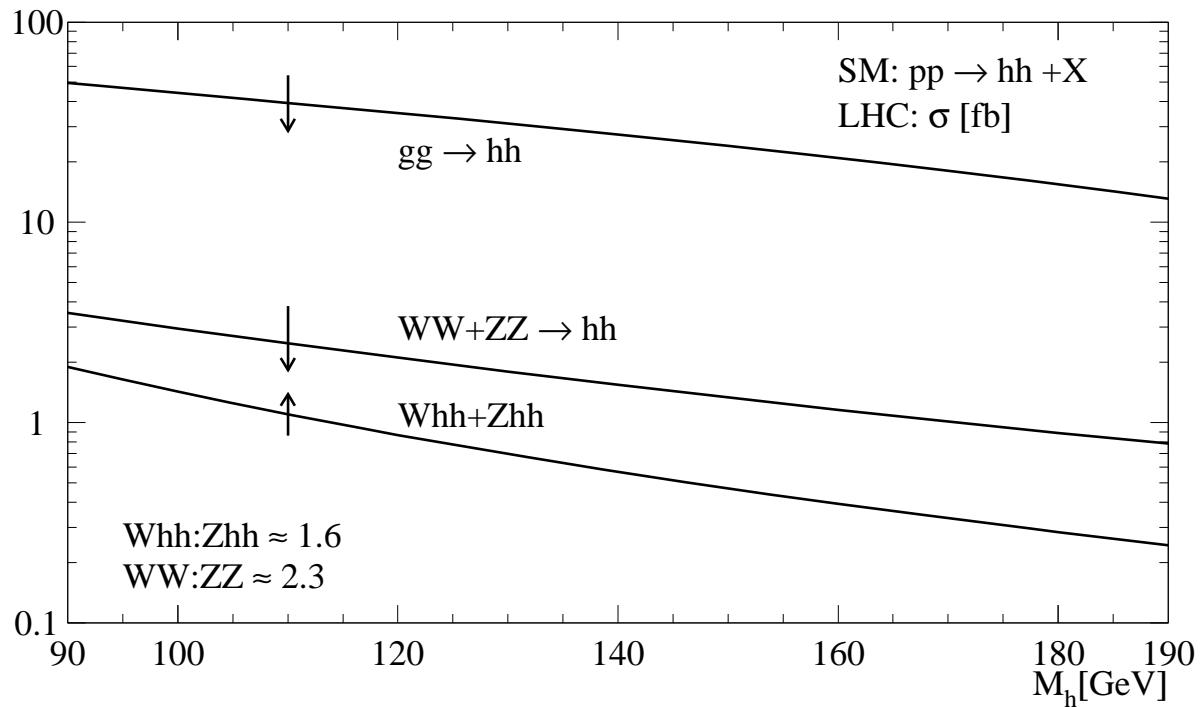
→  $\lambda, \tilde{\lambda}$  now free parameters

*Need direct observation of  $hh, hhh$*

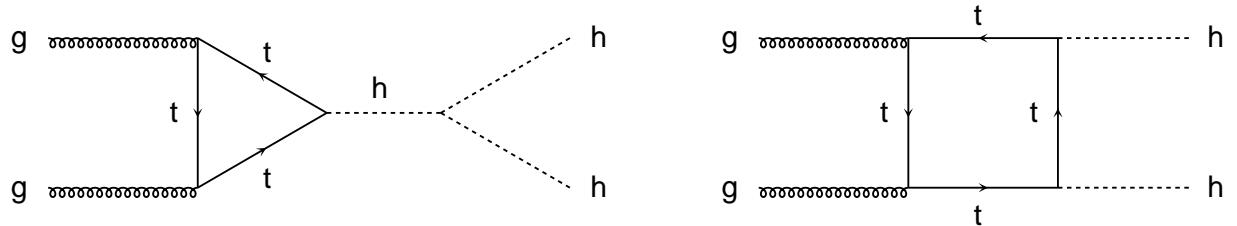
Our ultimate goal: measure Higgs potential  
→ proof of spontaneous symmetry breaking

# Measuring $\lambda$ via $hh$ production

[Djouadi, Kilian, Mühlleitner and Zerwas, 1999]



SM diagrams for largest contribution:



*interfere destructively!*

$gg \rightarrow hh$  @ LHC:  $\mathcal{O}(10k)$  events in Run I

$Zhh$  is largest  $hh$  rate at LC ( $\sqrt{s} < 1$  TeV):

$\approx 0.25\text{-}0.01$  fb for  $M_h \sim 100\text{-}200$  GeV:

250-10 events

## Measure $\sigma_{hh}$ , extract $\lambda$ from rate

But what is involved? Must also know:  
 $\text{BR}(b\bar{b}, \gamma\gamma, \tau^+\tau^-, \mu^+\mu^-, W^+W^-)$ ,  $Y_t$ ,  $J^{\text{CP}}$ , etc.

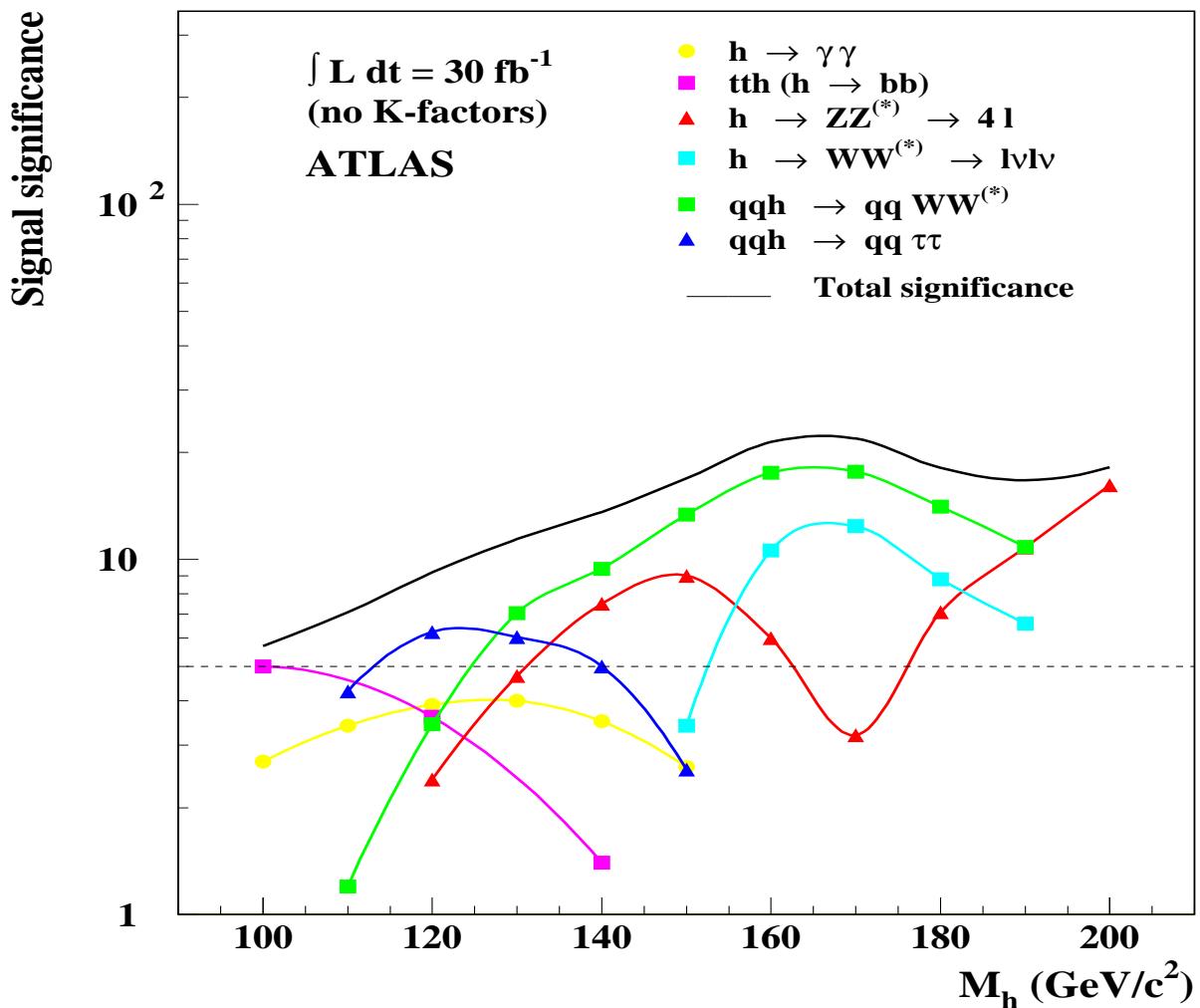
Q: Can these be determined at the LHC?  
(with useful precision?)

A: Yes; good enough for 1<sup>st</sup> measurement  
(Naturally, LC can do better for most, not all)

Determining multiple properties  
requires multiple measurements:  
→ measuring many Higgs channel rates  
→ prod./decay angular distributions

# LHC SM Higgs overview - latest from ATLAS

production	decay	$M_h$ range (GeV)	mass peak
$gg \rightarrow h$	$\gamma\gamma$	110-140	✓
	$W^+W^-$	<150-200+	(✓)
	$ZZ \rightarrow 4\ell$	>130	✓
$pp \rightarrow h jj$	$\tau^+\tau^-$	110-140	✓
	$W^+W^-$	120-200+	✓
	$ZZ$	120-200+	✓
	$\gamma\gamma$	110-140?	✓
	invisible	100-200	✗
	invisible	110-170	✗
$q\bar{q} \rightarrow Zh$	$b\bar{b}$	100-120?	✓
	$W^+W^-$	130-200+	✗



# *Can LHC measure $H$ couplings?*

Short answer: Yes, to a degree

Problem:

for  $M_H \lesssim 220$  GeV, no direct  $\Gamma_{tot}^H$  meas'mt

NEW:

**Max. Likelihood fit, 15 LHC Higgs channels**

[M. Dührssen, ATL-PHYS-2003-030]

- full treatment of systematic uncertainties
- Case 1: relative coups, no theory assumptions

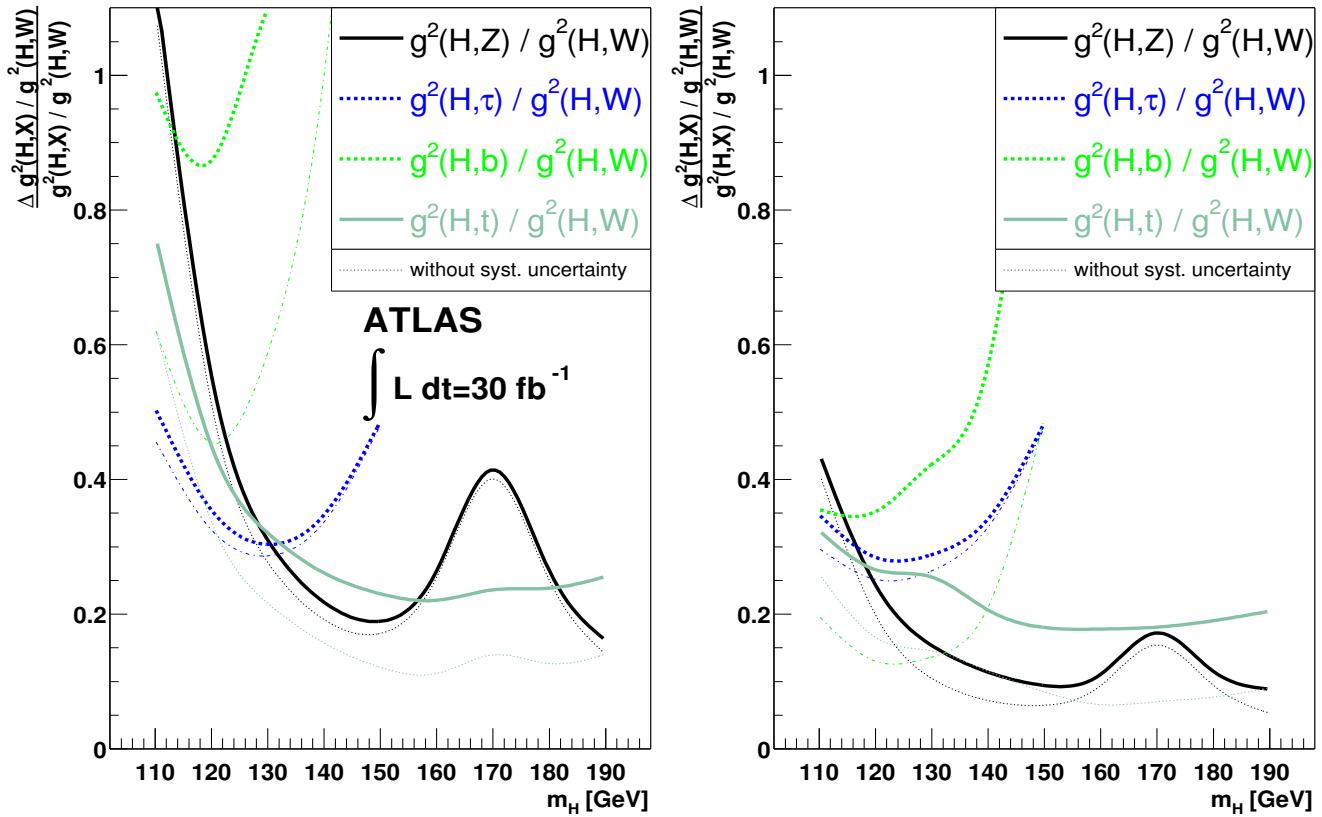
BUT gets absolute lower limit on  $\Gamma_{tot}^H$

- Case 2: absolute coups,  $\Gamma_{tot}^H$  assumption
- still (mostly) statistics limited; improve at SLHC

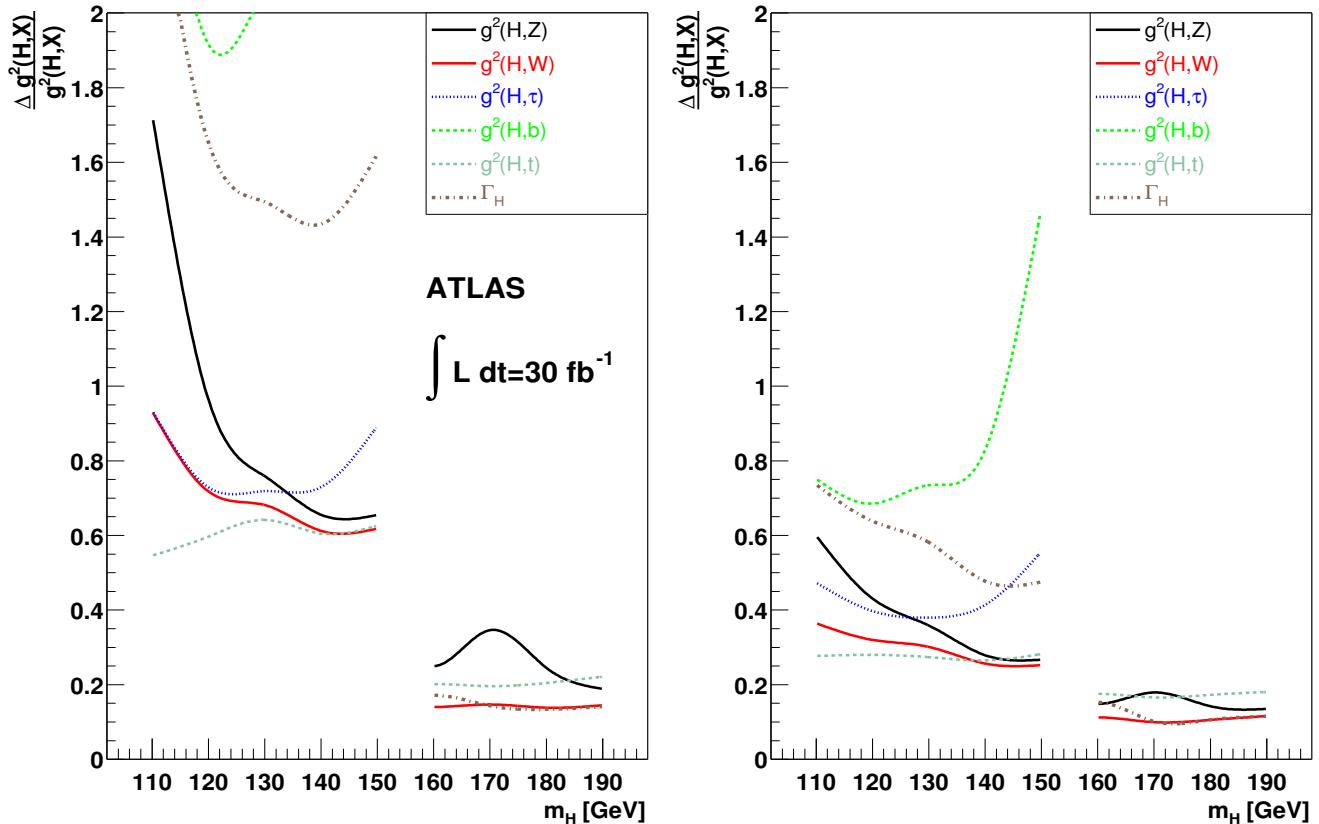
Ongoing study adds  $H \rightarrow invis$  channels,  
more WBF lumi reach, add'tl constraints...

[Dührssen, Heinemeyer, Logan, DR, Weiglein, Zeppenfeld]

# Case 1: rel. couplings, no theory assump.



# Case 2: absolute couplings, $\Gamma_{tot}^H$ assump.



SLHC would improve, espec. low  $M_H$ ,  
but QCD uncertainties limiting

Many important questions remain:

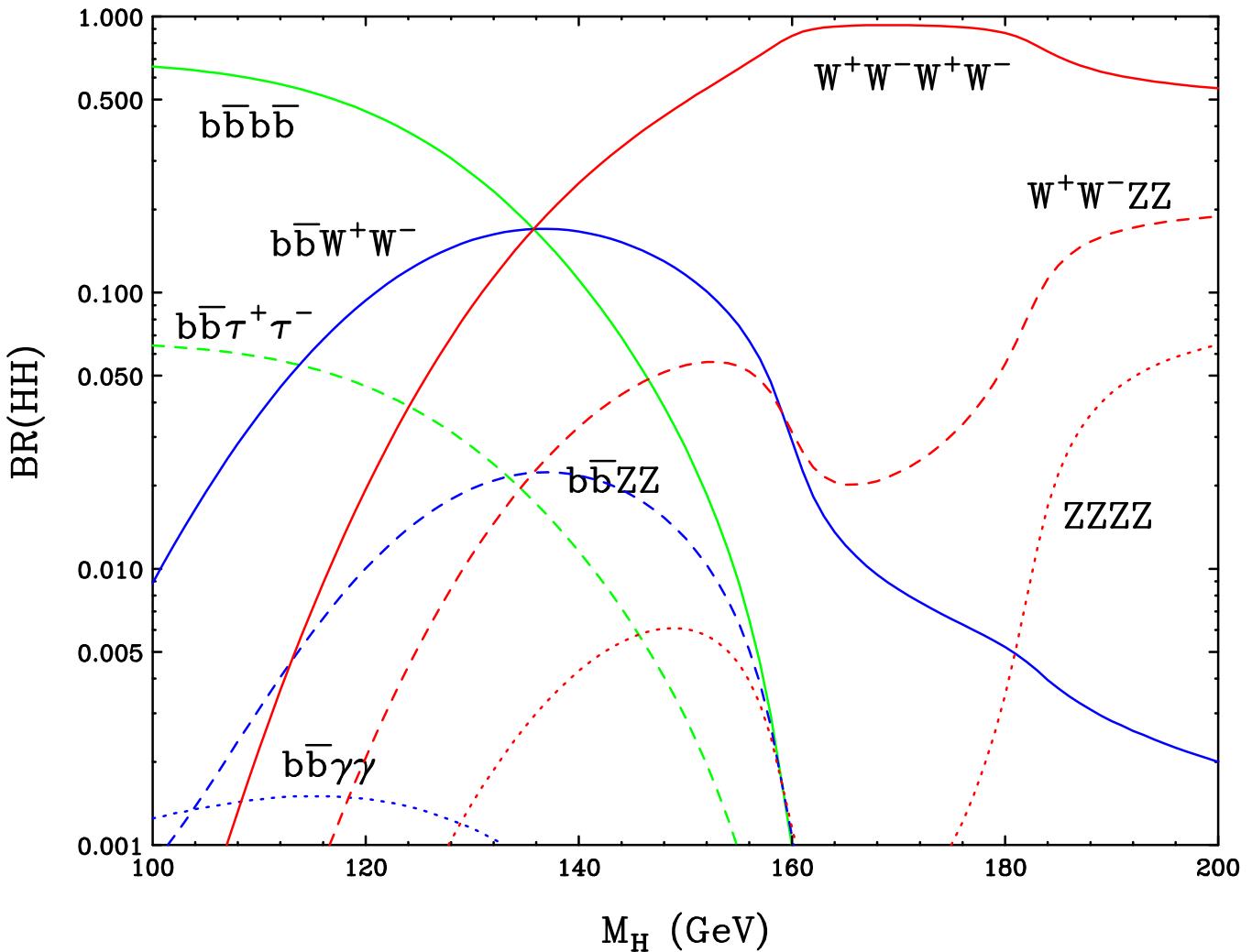
1.  $Y_t$  is perhaps most important coupling!
2. no 2<sup>nd</sup>-gen coup measured
3.  $Y_b/Y_\tau$  ratio only very poorly known
4. unknown (invisible?) Higgs decays?
5. anomalous Higgs QCD coups? ( $Y_c, \Gamma_g$ )

LC: precision values for  $g_Z, g_W, g_b, g_\tau, \Gamma_\gamma$   
& reasonably good values for  $g_c, \Gamma_g, \Gamma_{invis}$   
(note:  $g_c$  would be first/only 2<sup>nd</sup>-gen coup)  
► ultimately need precision LC input!

## Channels to measure $\sigma_{hh}$

Consider final state to observe  $hh$  events:

Higgs decays to SM pairs: kinematically-allowed  $f\bar{f}$ , or off-shell  $WW/ZZ$



*log plot!*

small  $M_h$ :  $4b$ ,  $b\bar{b}\tau^+\tau^-$ ,  $b\bar{b}\mu^+\mu^-$ ,  $b\bar{b}\gamma\gamma$

large  $M_h$ :  $4W \rightarrow$  multileptons

# *hh signals at the LHC*

[Baur,Plehn,DR, PRL(89)151801, PRD(67)033003]

For  $M_h$  large, examine  $4W$  final states

$hh \rightarrow W^+W^-W^+W^-$  has myriad decays;  
choose multilepton final states for trigger  
and QCD background rejection:

$$\ell^\pm\ell^\pm + 4j \quad , \quad \ell^\pm\ell^\pm\ell^\mp + 2j$$

note: no mass reconstruction!

principal backgrounds are

$WWWjj$ ,  $t\bar{t}W$ ,  $t\bar{t}j$ ,  $t\bar{t}Z/\gamma^*$ ,  $WZ + 4j$

must also consider

$t\bar{t}t\bar{t}$ ,  $4W$ ,  $WW + 4j$ ,  $WWZjj$

as well as

DPS and overlapping events

→ we calculate all of these

Analysis considers NLO effects,  
minimal detector effects and realistic  $\epsilon_{ID}$

# Notes on signal

Uses LO exact (finite  $m_t$ ) matrix elements;  
NLO via K-factor (NLO/LO  $m_t \rightarrow \infty$  results)

[Dawson, Dittmaier & Spira, PRD(58)115012]

# Notes on backgrounds

## 1. $t\bar{t}j$ : TSA approximation

integrate from  $p_T(j) > 2$  GeV,  
regulate with exponential suppression

$$d\sigma_{t\bar{t}j}^{TSA} = d\sigma_{t\bar{t}j}^{TL} (1 - e^{-p_T^2(j)/p_{TSA}^2})$$

and normalize with  $\sigma_{t\bar{t}j}^{TSA} \equiv \sigma_{t\bar{t}}^{NLO}$

## 2. all backgrounds using MadGraph (LO)

incl. all interferences, decays, spin corr.

## 3. double parton scattering (DPS)

$$\sigma_{DPS} = \frac{\sigma_1 \sigma_2}{\sigma_{eff}} \quad w/ \sigma_{eff} \sim 15 \text{ mb}$$

and P.S. restriction ( $x_i$ )

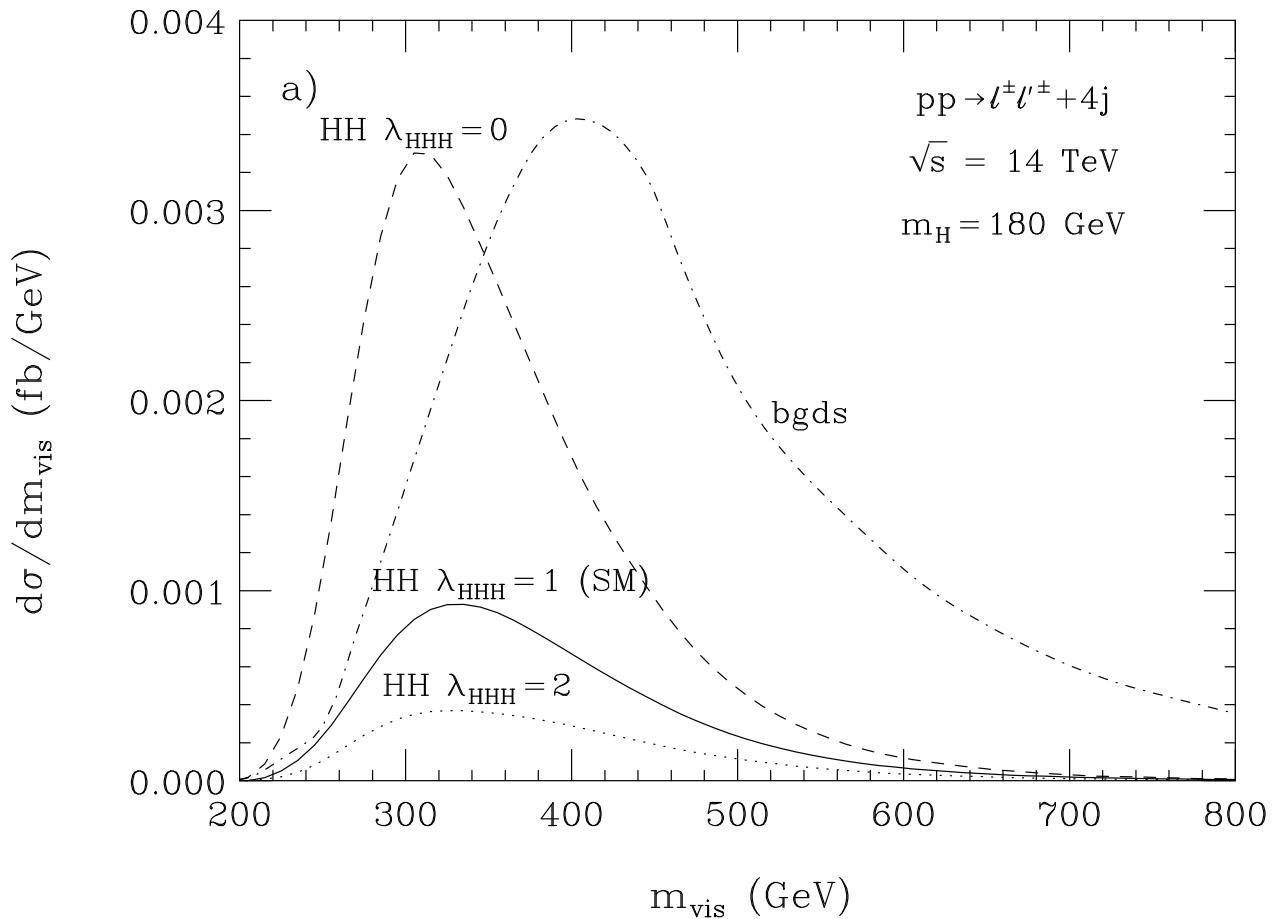
## 4. overlapping events

$$\sigma_{ov} = \frac{1}{2} \sigma_1 \sigma_2 \mathcal{L}_{bc}, \quad \mathcal{L}_{bc} = \mathcal{L} \Delta \tau \text{ fn. of lumi}$$

# Signal characteristics

$hh$  is 2-body:  $m_{vis}$  peak near threshold

$$m_{vis}^2 = [\sum_i E_i]^2 - [\sum_i \mathbf{p}_i]^2$$



Variation  $0 < \lambda < 2\lambda_{SM}$ :

significant  $\sigma_{hh}$  change at low  $m_{vis}$

$\chi^2$  test on distribution:

- signal  $K_{NLO} = 1.65(1.35)$  for LHC(VLHC)
- bkg option 1:  $K_{NLO} = 1.0$ ,  $\delta B = 30\%$
- bkg option 2:  $K_{NLO} = 1.3$ ,  $\delta B = 10\%$
- select more conservative bound

## Cross sections for $pp \rightarrow hh \rightarrow 4W$

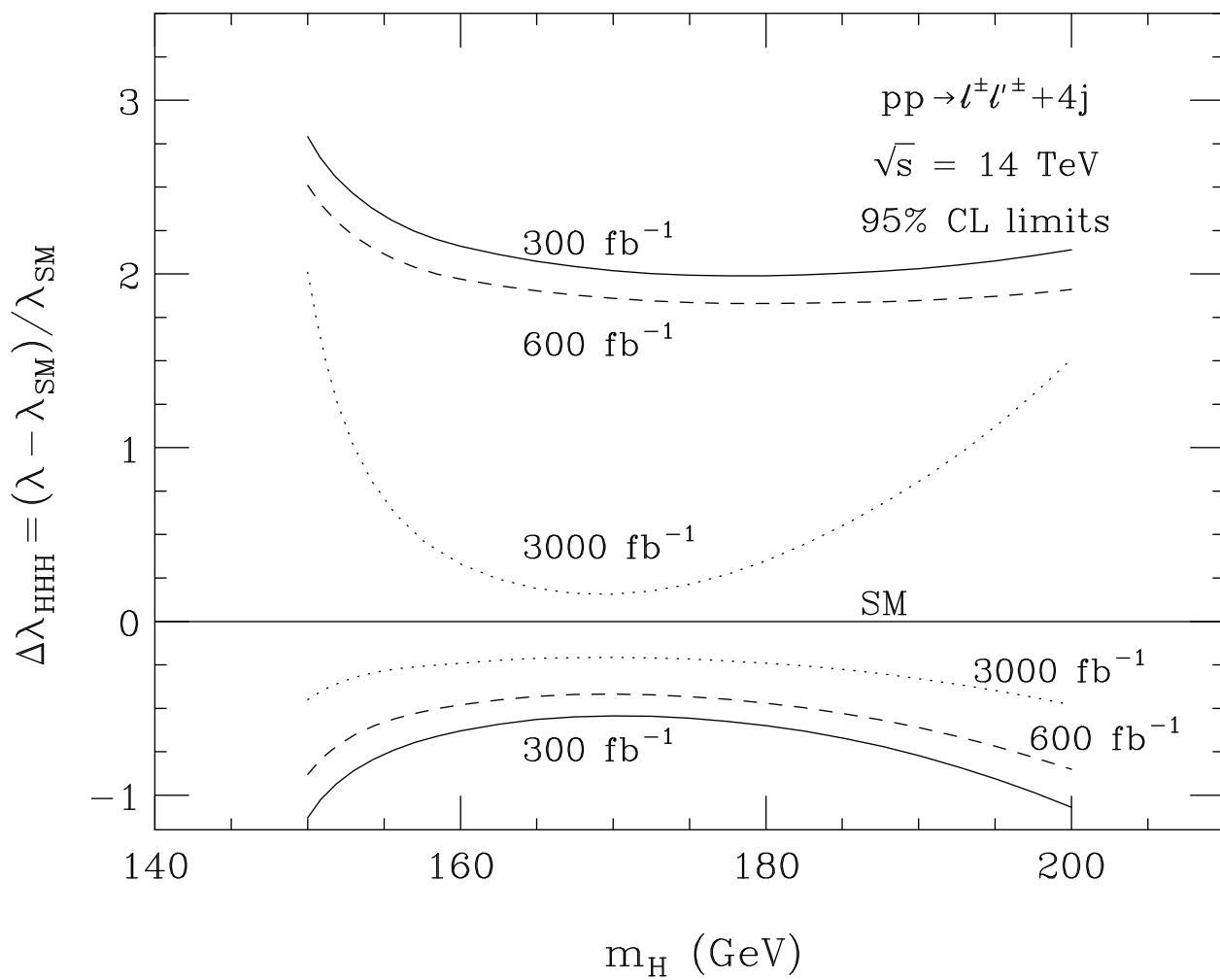
$\ell^\pm\ell^\pm + 4j$ ,  $M_h = 160$  GeV, incl. cuts & BRs

	$hh$	$WWWjj$	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}j$	$WZ+4j$	$WW+4j$	$t\bar{t}t\bar{t}$	pileup	$\mathcal{B}_{tot}$
LHC	0.19	0.49	0.22	0.05	0.08	0.15	0.005	0.002	$\sim 0.03$	1.03
VLHC	15.8	20.4	5.8	7.4	7.7	8.1	0.13	6.13	$\sim 20$	75.7

A few things to note:

- ▶  $S/B \sim 1/5$  quite respectable
  - ▶ DPS & OV relevant only @ SLHC  
and data will soon refine estimates
- NLO  $t\bar{t}j$  coming soon
- NLO  $t\bar{t}W$  needed and easily possible
- NLO  $WWWjj$  in principle possible

# *Results for $hh \rightarrow 4W$ @ LHC*



1. LHC excludes  $\lambda = 0$  at  $\geq 95\%$  c.l. w/  
 $300 \text{ fb}^{-1}$  for  $150 < M_h < 200 \text{ GeV}$
2. Double lumi improves bounds 10 – 25%
3. SLHC  $\lambda$  at 20 – 30% ( $3000 \text{ fb}^{-1}$ )
4. LC would compete with SLHC

# ATLAS study of $hh \rightarrow 4W$

ATLAS study null result: “cannot do it”

Not unexpected! - consider:

1. finite- $m_t$  code, but missed physics
  - no  $\Delta R$  cut used
  - no  $m_{\text{vis}}$  peak used, no  $\chi^2$  fit
2. incorrect signal normalization  
[Dawson,Dittmaier,Spira, PRD(58)115012]
3. incorrect generation of  $t\bar{t}j$  background  
→ huge effect on signal retention

ATLAS reinvestigating [Jakobs & Dahlhoff, Freiburg]

Issues to be resolved:

1.  $t\bar{t}j$   $p_T(\ell)$  dists: semilep.  $b$  decay
2. ISF/FSR and min. bias jets affecting  $m_{\text{vis}}$   
→ degradation or overall shift?
3. systematics from  $\delta Y_t$ ,  $\delta \text{BR}(WW)$ , etc.

## Issue #1: Semilep. $b$ decays in $t\bar{t}j$ events

First estimate only  $b \rightarrow c\ell\nu$

⇒ underestimates rate for given  $\ell$  isol.

( $b \rightarrow (\pi, \rho)\ell\nu$  has more phase space)

Better method:

$$\sigma_{t\bar{t}j}^{tot} = \sigma_{t\bar{t}j}^{b \rightarrow c} + 0.17 \cdot \sigma_{t\bar{t}j}^{b \rightarrow \pi} + 0.83 \cdot \sigma_{t\bar{t}j}^{b \rightarrow \rho}$$

1.  $\ell$  isol. cone 0.4 &  $p_T(c, \pi, \rho) < 3$  GeV:

$$\sigma_{t\bar{t}j}^{tot} \uparrow \times 10$$

$$\sigma_{tot} \uparrow \times 2 - \text{problem!!}$$

2.  $\ell$  isol. cone 0.4 &  $p_T(c, \pi, \rho) < 1$  GeV

$$\sigma_{t\bar{t}j}^{tot} \uparrow \times 3$$

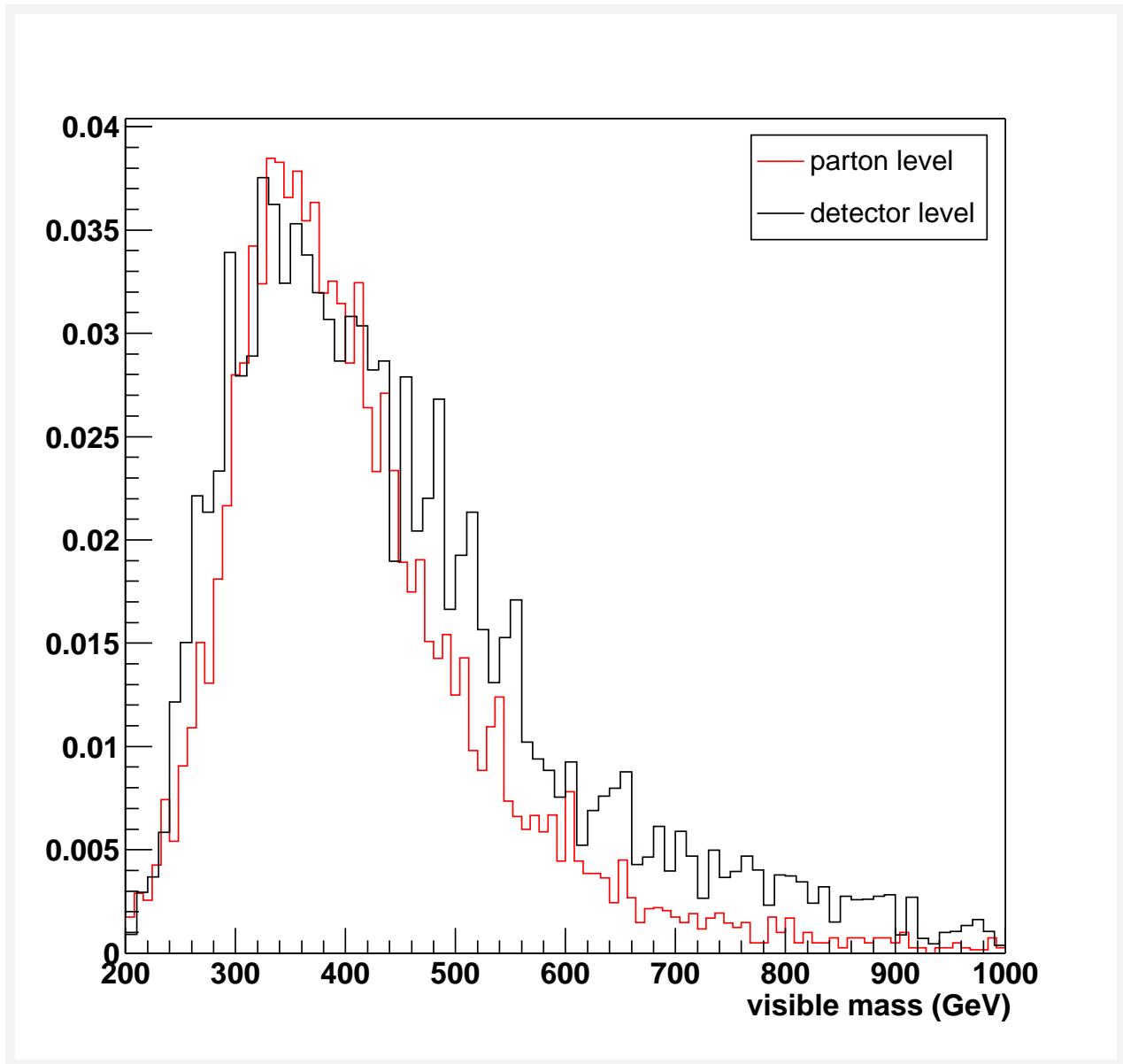
$$\sigma_{tot} \uparrow \times 20\% - \text{limits worse by 20\%}$$

→ ATLAS (Freiburg) new **preliminary** result:

opt. 2 ok, agree w/in 40%!

## Issue #2: ISR/FSR/min. bias and $m_{vis}$

ATLAS says:



Does not appear to be a major issue!

→ working w/ Freiburg ATLAS group for full sim.

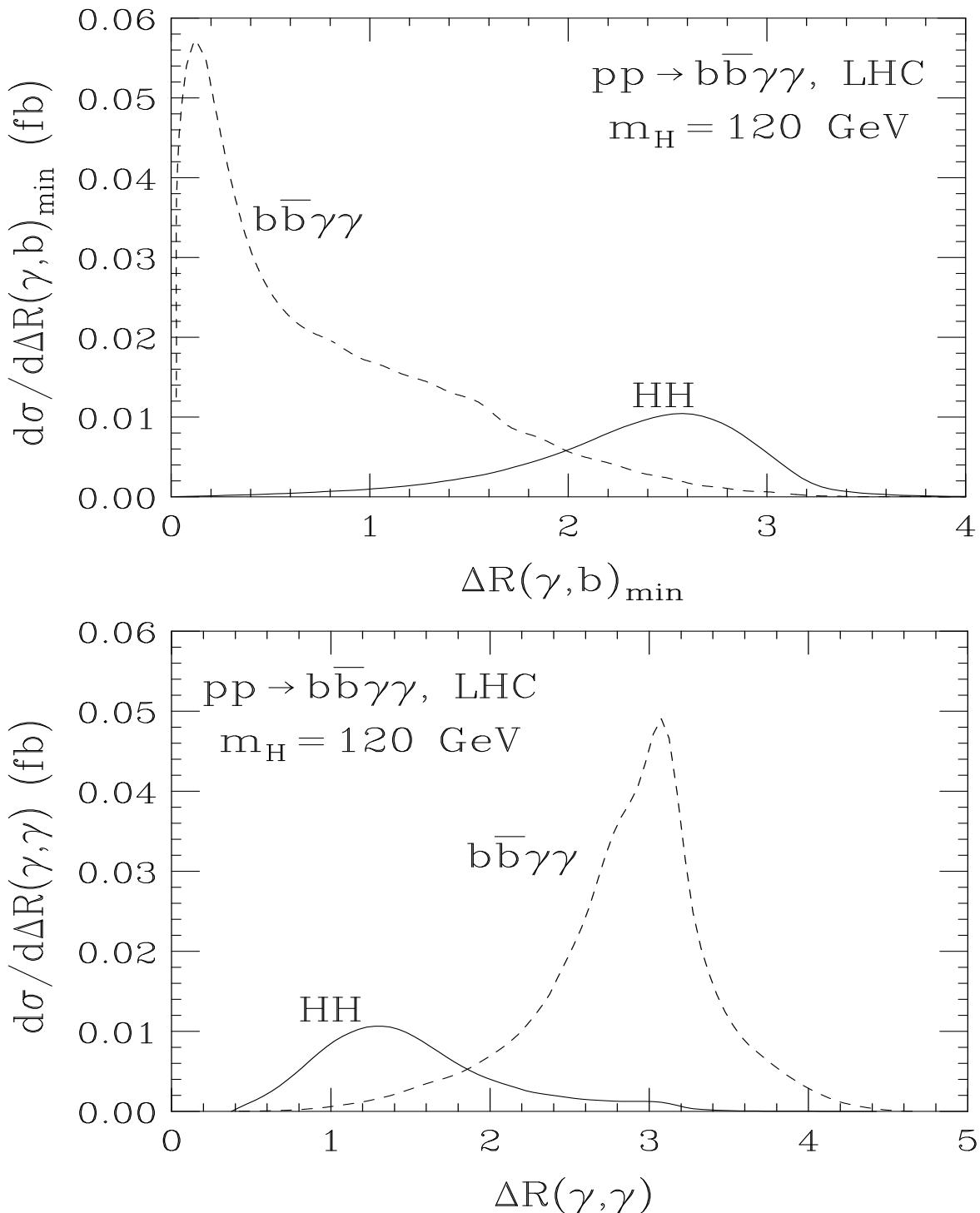
## LHC, $M_h < 150$ GeV: use rare mode $b\bar{b}\gamma\gamma$

Backgrounds to consider:

- $b\bar{b}\gamma\gamma$
- $c\bar{c}\gamma\gamma$  - 1 or 2 fake  $b$  jets
- $b\bar{b}j\gamma$  - 1 fake  $\gamma$
- $c\bar{c}j\gamma$  - 1 or 2 fake  $b$ -jets, 1 fake  $\gamma$
- $jj\gamma\gamma$  - 1 or 2 fake  $b$ -jets
- $b\bar{b}jj$  - 2 fake  $\gamma$
- $c\bar{c}jj$  - 1 or 2 fake  $b$ -jets, 2 fake  $\gamma$
- $jjj\gamma$  - 1 or 2 fake  $b$ -jets, 1 fake  $\gamma$
- $jjjj$  - 1 or 2 fake  $b$ -jets, 2 fake  $\gamma$
- $Hjj$  - 1 or 2 fake  $b$ -jets, or 2 fake  $\gamma$
- $Hj\gamma$  - 1 fake  $\gamma$

	$\epsilon_\gamma$	$\epsilon_\mu$	$P_{c \rightarrow b}$	$P_{j \rightarrow b}$	$P_{j \rightarrow \gamma}^{hi}$	$P_{j \rightarrow \gamma}^{lo}$
LHC	80%	90%	1/13	1/140	1/1600	1/2500
SLHC	80%	90%	1/13	1/23	1/1600	1/2500
VLHC	80%	90%	1/13	1/140	1/1600	1/2500

Again use  $\chi^2$  test on  $m_{vis}$ , but need  
way to distinguish S & B - angular dists:



→ may allow “sideband” bkg calibration,  
since NLO calc's not available

DPS and OV potentially very large!

But clever trick can completely eliminate...

→  $p_T$  balance rejection criteria

E.g.:  $b\gamma + b\gamma$  (jet fakes) overlapping events

$$|\vec{p}_T(b) + \vec{p}_T(\gamma_1)|, |\vec{p}_T(\bar{b}) + \vec{p}_T(\gamma_2)| < 20 \text{ GeV}$$

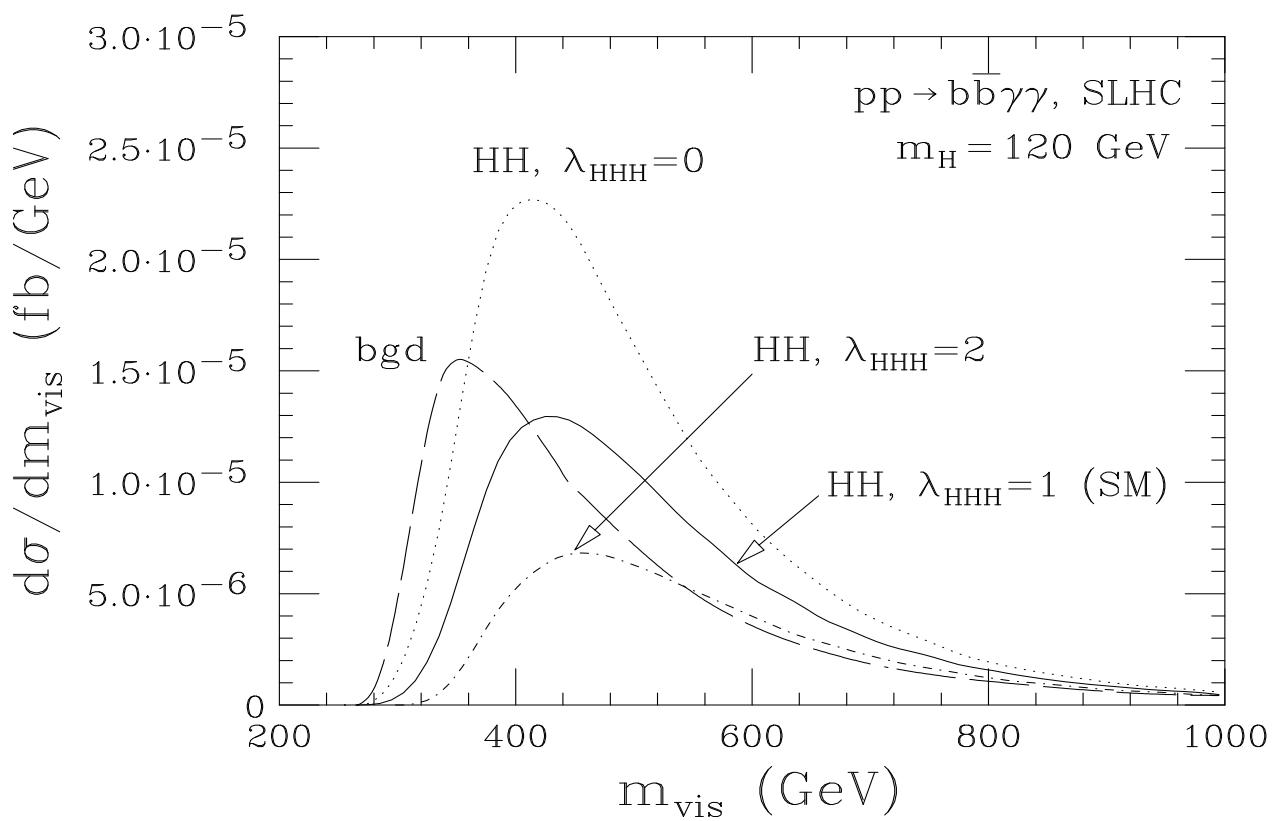
and

$$|\vec{p}_T(\bar{b}) + \vec{p}_T(\gamma_1)|, |\vec{p}_T(b) + \vec{p}_T(\gamma_2)| < 20 \text{ GeV}$$

These cuts reduce DPS + mult. int. to zero,  
signal affected at < 10% level  
(we include Gaussian momentum smearing)

► used by CDF, so we know it works!

# $pp \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$ signal v. bkg



# events expected for  
 LHC, SLHC, VLHC (600,6000,600  $\text{fb}^{-1}$ ):

	$hh$	$b\bar{b}\gamma\gamma$	$c\bar{c}\gamma\gamma$	$b\bar{b}\gamma j$	$c\bar{c}\gamma j$	$jj\gamma\gamma$	$b\bar{b}jj$	$c\bar{c}jj$	$\gamma jjj$	$jjjj$	$\sum(\text{bkg})$	S/B
LHC	6	2	1	1	0	5	0	0	1	1	11	1/2
SLHC	21	6	0	4	0	6	1	0	1	1	20	1/1
VLHC	486	40	70	60	29	137	30	6	36	40	448	1/1

1  $b$ -tag @ LHC, VLHC

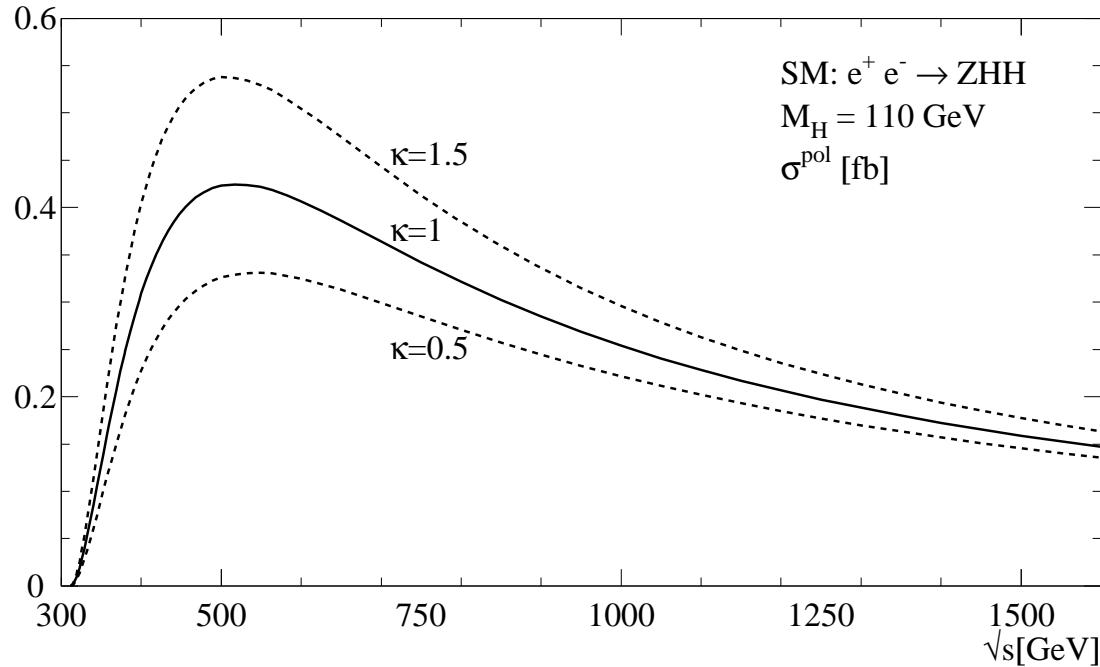
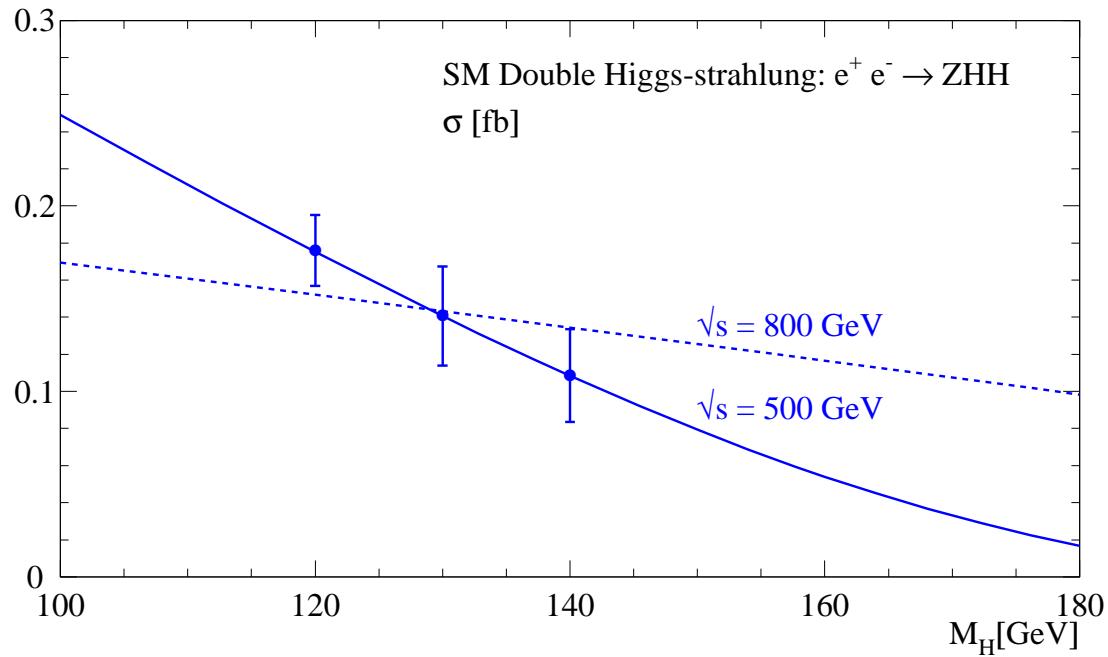
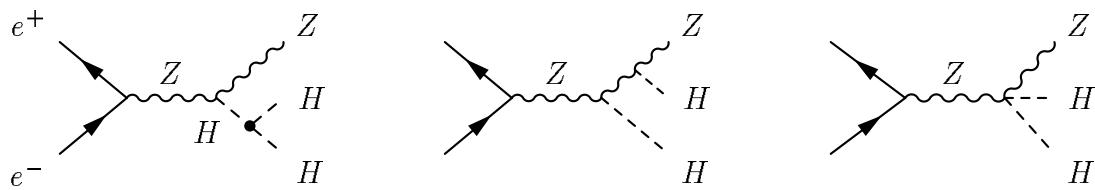
2  $b$ -tags @ SLHC (to overcome low fake rejection)

## $hh \rightarrow b\bar{b}\gamma\gamma$ results

machine lumi	$m_H = 120 \text{ GeV}$		$m_H = 140 \text{ GeV}$	
	norm	B sub.	norm	B sub.
LHC $600 \text{ fb}^{-1}$	+1.6	+0.94	—	—
	-1.1	-0.74	—	—
SLHC $6000 \text{ fb}^{-1}$	+0.74	+0.52	+1.4	+0.76
	-0.62	-0.46	-0.8	-0.58
VLHC $1200 \text{ fb}^{-1}$	+0.30	+0.26	+0.62	+0.36
	-0.28	-0.22	-0.50	-0.32

- VLHC competitive with CLIC
- significant improvement w/ bkg subtraction

# $e^+e^- \rightarrow ZHH$

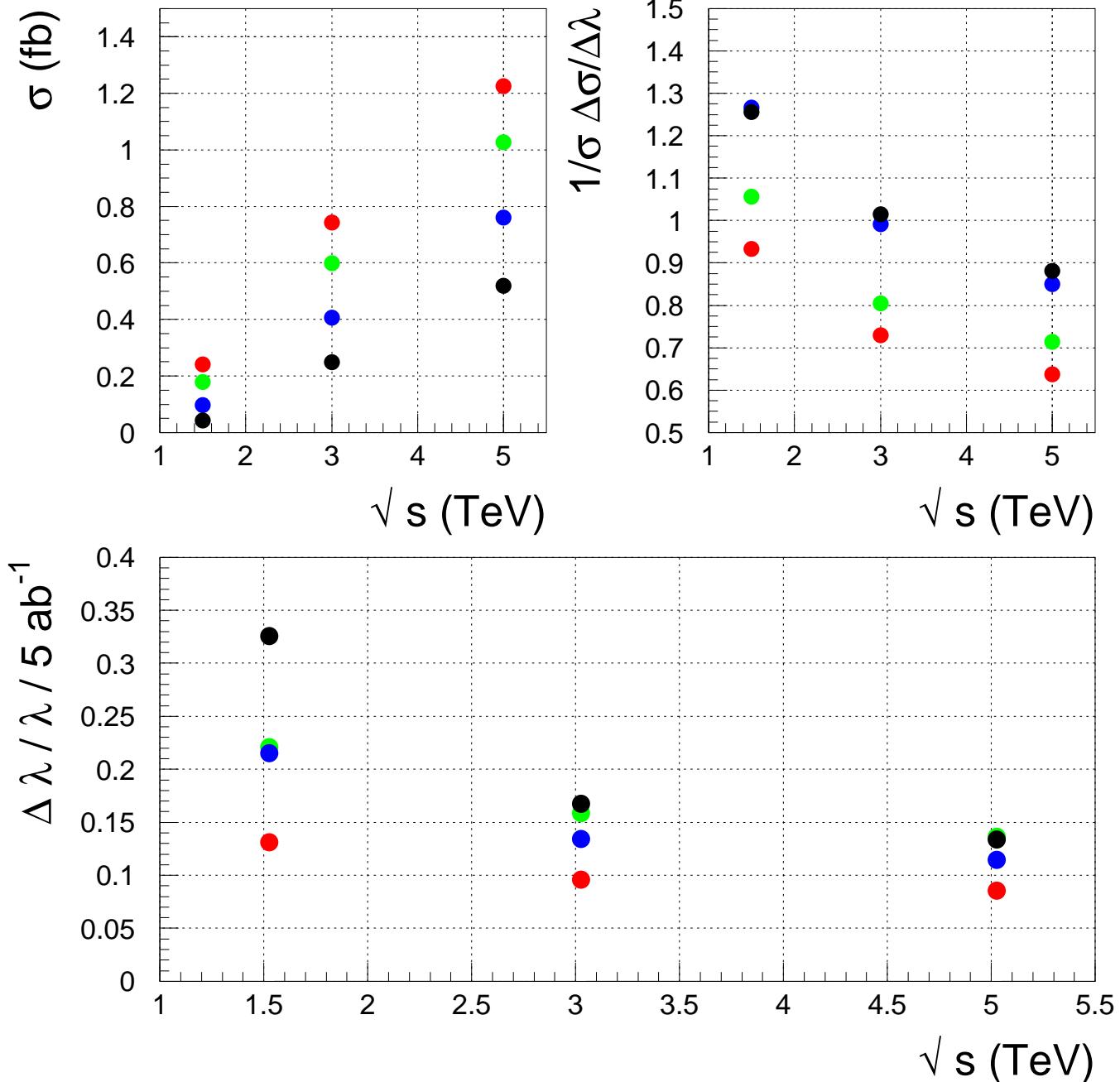


►  $\frac{\Delta\lambda}{\lambda} \approx 20\text{-}50\%$  for  $120 < M_h < 140$  GeV

[Battaglia & DeRoeck, WIN'03]

$$e^+ e^- \rightarrow \nu \bar{\nu} H H$$

[Battaglia & DeRoeck, WIN03]



$$M_h = 120, 140, 180, 240$$

- LC upgrade ok, but need CLIC to do best
- limits limited by washing-out of  $hhh$  diagram at large  $\sqrt{s}$

## *EW corrections to $\lambda$ in SM*

[Kanemura *et al.*, PLB(558)157]

(also analyzes for 2HDMs)

→ leading 1-loop top quark effects:

$$\lambda_{hhh}^{eff} = \frac{M_h^2}{2v^2} \left[ 1 - \frac{N_C}{3\pi^2} \frac{m_t^4}{v^2 M_h^2} + \dots \right]$$

( $M_h, m_t$  are physical masses)

$\sim -10\%$  for  $M_h = 120$  GeV

$\sim -4\%$  for  $M_h = 180$  GeV

→ take into account, but no access @ (S)LHC

## Deviations to $\lambda, \tilde{\lambda}$ in SM

With 1 doublet, only 2 poss. D6 operators:

[Buchmüller & Wyler, NPB(268)621]

$$\mathcal{O}_1 = \frac{1}{2} \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi) \text{ & } \mathcal{O}_2 = -\frac{1}{3} (\Phi^\dagger \Phi)^3$$

for the effective Lagrangian contribution

$$\mathcal{L}_{6D,\Phi} = \sum_{i=1}^2 \frac{f_i}{\Lambda^2} \mathcal{O}_i , \quad f_i > 0$$

This modifies the 3,4-pt. self-coups:

$$\lambda_{hhh} = \frac{3m_H^2}{v} \left[ \left( 1 - \frac{f_1 v^2}{2\Lambda^2} + \frac{2f_2 v^2}{3\Lambda^2} \frac{v^2}{m_H^2} \right) + \frac{2f_1 v^2}{3m_H^2} \sum_{i<j}^3 p_i \cdot p_j \right]$$

$$\lambda_{hhhh} = \frac{3m_H^2}{v^2} \left[ \left( 1 - \frac{f_1 v^2}{\Lambda^2} + \frac{4f_2 v^2}{\Lambda^2} \frac{v^2}{m_H^2} \right) + \frac{2f_1 v^2}{3m_H^2} \sum_{i<j}^4 p_i \cdot p_j \right]$$

[Barger et al., PRD(67)115001, analysed for LC]

and normal modes not affected

(not true for 2HDM - much more complicated)

→ we have not analyzed anomalous coups

## Other D6 op.'s for $M_h > 140$ GeV

$$O_{WW} = (\phi^\dagger \phi) [W_{\mu\nu}^+ W^{-\mu\nu} + \frac{1}{2} W_{\mu\nu}^3 W^{3\mu\nu}]$$

$$O_{BB} = (\phi^\dagger \phi) B_{\mu\nu} B^{\mu\nu}$$

$$\begin{aligned} O_{BW} = & B^{\mu\nu} [(\phi^\dagger \sigma^3 \phi) W_{\mu\nu}^3 + \sqrt{2} [(\phi^\dagger T^+ \phi) W_{\mu\nu}^+ \\ & + (\phi^\dagger T^- \phi) W_{\mu\nu}^-]] \end{aligned}$$

$$\begin{aligned} O_W = & (D^\mu \phi)^\dagger [\sigma^3 (D^\nu \phi) W_{\mu\nu}^3 \\ & + \sqrt{2} [T^+ (D^\nu \phi) W_{\mu\nu}^+ + T^- (D^\nu \phi) W_{\mu\nu}^-]] \end{aligned}$$

$$O_B = (D^\mu \phi)^\dagger (D^\nu \phi) B_{\mu\nu}$$

$$O_{\Phi,1} = (D_\mu \phi)^\dagger \phi \phi^\dagger (D^\mu \phi)$$

→ give anomalous mom.-dep.

$hhWW, hhZZ, hhZA, hhAA$  vertices

But highly constrained by  $S, \rho, g_{VVV}$ !

[R. Szalapski et al., no updates past '98]

study in progress, not expected to be significant

[Kilian,DR]

## Other $D6$ op.'s for $M_h < 140$ GeV

[Kilian,DR, in progress]

$$O_{d\phi} = (\phi^\dagger \phi)(\bar{q} d \phi)$$

$$O_{\phi q}^{(1)} = i(\phi^\dagger D_\mu \phi)(\bar{q} \gamma^\mu q)$$

$$O_{\phi q}^{(3)} = i(\phi^\dagger D_\mu \sigma^i \phi)(\bar{q} \gamma^\mu \sigma^i q)$$

$$O_{\phi d} = i(\phi^\dagger D_\mu \phi)(\bar{d} \gamma^\mu d)$$

$$O_{\phi\phi} = i(\phi^\dagger \epsilon D_\mu \phi)(\bar{u} \gamma^\mu u)$$

$$O_{Dd} = (\bar{q} D_\mu d) D^\mu \phi \quad O_{\bar{D}d} = (D_\mu \bar{q} d) D^\mu \phi$$

$$O_{dW} = (\bar{q} \sigma^{\mu\nu} \sigma^i d) \phi W_{\mu\nu}^i$$

$$O_{dB} = (\bar{q} \sigma^{\mu\nu} d) \phi B_{\mu\nu}$$

→ some constrained by  $Z b\bar{b}, \gamma b\bar{b}$  coups

→ others give interesting rare decays:

$$h \rightarrow b\bar{b}Z, b\bar{b}\gamma, \dots$$

- ▶ NOT a concern for  $\lambda$  measurement  
since no mass peak for extra  $b\bar{b}$  at  $M_h$

## 2HDM (incl. SUSY) Higgses?

→ driven by parameters  $M_A$  and  $\tan \beta$ ,  
ratio of up/down vevs  $v_2, v_1$

(small or large  $\tan \beta$  preferred,  $\sim 3$  or  $\sim 30$ )

Five states to observe:  $h, H, A, H^\pm$ :

- $h$  CP-even, light, typically SM-like
- $H$  CP-even, typically heavy
- $A$  CP-odd, typically degenerate w/  $H$
- $H^\pm$  typically degenerate w/  $H, A$

Again, consider

$pp \rightarrow gg \rightarrow \Phi_i\Phi_j, \Phi_i = h, H, A.$

# MSSM Higgs potential and self-couplings

---

$$\begin{aligned}
V(\phi_1, \phi_2) = & \lambda_1 (\phi_1^\dagger \phi_1 - v_1^2)^2 + \lambda_2 (\phi_2^\dagger \phi_2 - v_2^2)^2 \\
& + \lambda_3 \left[ (\phi_1^\dagger \phi_1 - v_1^2) + (\phi_2^\dagger \phi_2 - v_2^2) \right]^2 \\
& + \lambda_4 \left[ (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) - (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) \right] \\
& + \lambda_5 \left[ \text{Re}(\phi_1^\dagger \phi_2) - v_1 v_2 \cos \xi \right]^2 \\
& + \lambda_6 \left[ \text{Im}(\phi_1^\dagger \phi_2) - v_1 v_2 \sin \xi \right]^2
\end{aligned}$$

all  $\lambda_i$  real,  $\xi$  represents  $CP$  violation

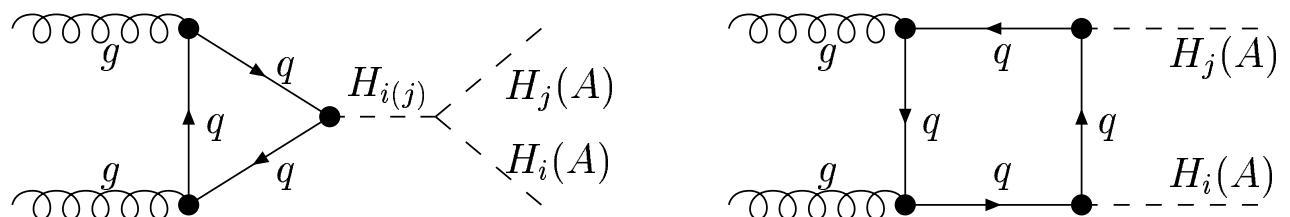
Convert to  $\lambda_{\phi_i \phi_j \phi_k}$  notation:

$$\begin{aligned}
\lambda_{hhh} &= 3 \cos 2\alpha \sin(\beta + \alpha) + \frac{3\epsilon}{M_Z^2} \frac{\cos^3 \alpha}{\sin \beta} \\
\lambda_{Hhh} &= 2 \sin 2\alpha \sin(\beta + \alpha) - \cos 2\alpha \cos(\beta + \alpha) + \frac{3\epsilon}{M_Z^2} \frac{\sin \alpha \cos^2 \alpha}{\sin \beta} \\
\lambda_{HHh} &= -2 \sin 2\alpha \cos(\beta + \alpha) - \cos 2\alpha \sin(\beta + \alpha) + \frac{3\epsilon}{M_Z^2} \frac{\sin^2 \alpha \cos \alpha}{\sin \beta} \\
\lambda_{HHH} &= 3 \cos 2\alpha \cos(\beta + \alpha) + \frac{3\epsilon}{M_Z^2} \frac{\sin^3 \alpha}{\sin \beta} \\
\lambda_{hAA} &= \cos 2\beta \sin(\beta + \alpha) + \frac{\epsilon}{M_Z^2} \frac{\cos \alpha \cos^2 \beta}{\sin \beta} \\
\lambda_{HAA} &= -\cos 2\beta \cos(\beta + \alpha) + \frac{\epsilon}{M_Z^2} \frac{\sin \alpha \cos^2 \beta}{\sin \beta}
\end{aligned}$$

where  $\epsilon = \frac{3G_F}{\sqrt{2}\pi^2} \frac{m_t^4}{\sin^2 \beta} \log \left[ 1 + \frac{M_S^2}{m_t^2} \right]$ ,

$M_S$  common squark mass,  $\alpha$  ( $h, H$ ) mixing angle,  
and all couplings normalized to  $\sqrt{\sqrt{2}G_F} M_Z^2$

## MSSM $pp \rightarrow \phi_i \phi_j$ @ large $\tan \beta$



$g_{Hdd,Add} \propto \tan \beta$ , but not  $\lambda$ !

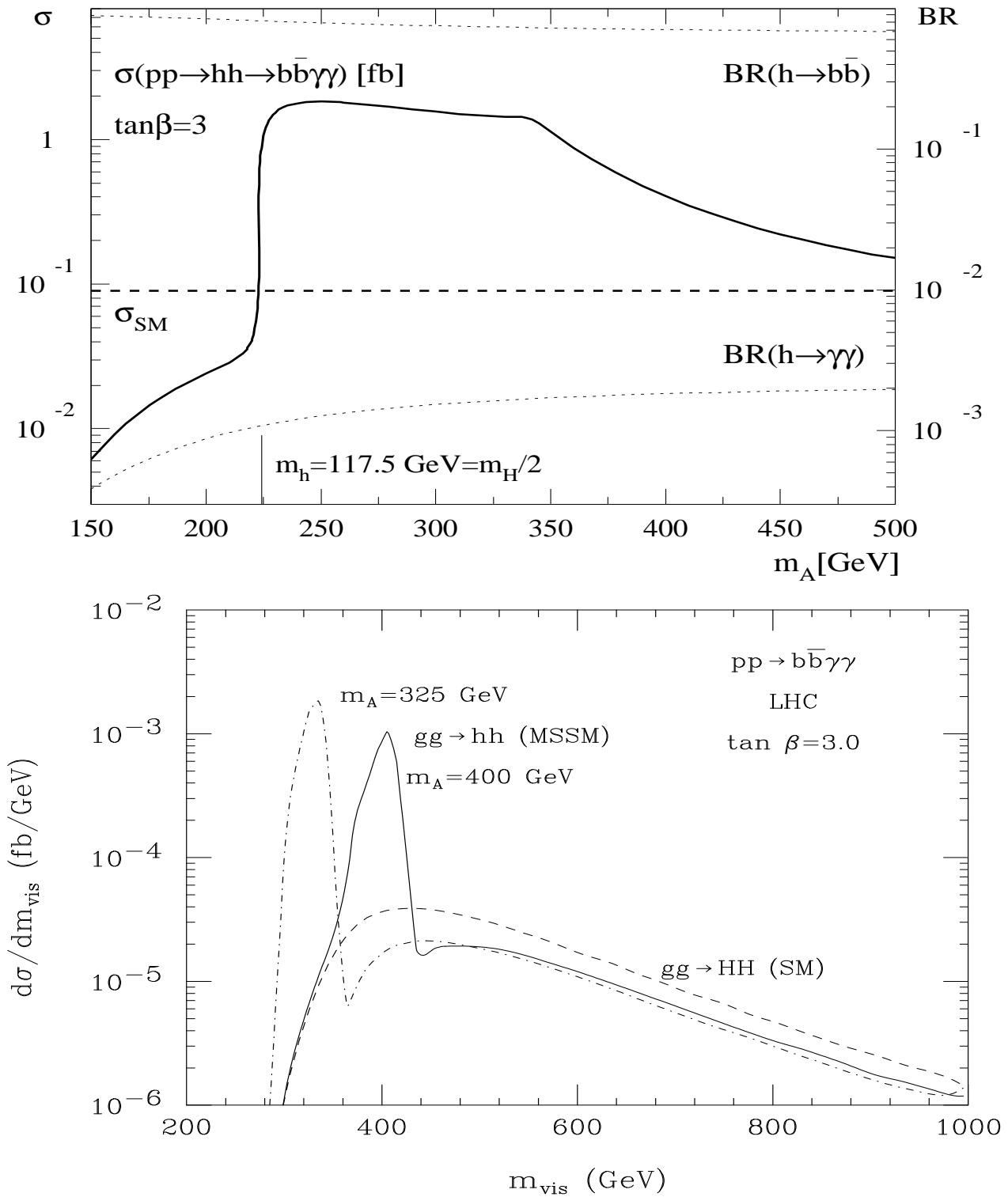
$\therefore$  box wins out by  $\tan \beta^2$

$\rightarrow$  measurement useless

In addition, typically swamped by  $H/Ab\bar{b}$

large  $\tan \beta$  region pretty hopeless...

# $MSSM \, pp \rightarrow \phi_i \phi_j, \text{ small } \tan \beta$ [Baur, Plehn, DR]



May be only non-SM Higgs evidence @ (S)LHC

Measuring  $\lambda_i$ 's directly may not be possible!  
(rely on  $M_{h_i}$ 's,  $\tan \beta$ , etc.)

## MSSM $\mu$ problem and the NMSSM

MSSM superpotential has strange term:

$$\mu H_u H_d$$

- $\mu$  is dimensionful [GeV]
- $|\mu|$  must be  $v$ -sized  $\rightarrow$  fine-tuning again!

Possible solution: “NMSSM”

$$\mu \longrightarrow \Phi_s = (v_s + s) + ia \quad \text{complex singlet}$$

$\therefore |\mu| = v_s$ , naturally EW-scale

Phenomenological implications:

- 2 extra physical Higgs bosons (7 total)
- 1 extra neutralino (5 total)
- $a$  is possible Peccei-Quinn axion

**BIG PROBLEM: LHC can't see extra states!**

→ implies determining nature of SUSY  
would require a new  $e^+e^-$  collider  
(well, we knew that anyway...)

## *hhh at the LHC/SLHC/VLHC*

Only way to measure  $\lambda_{4h}$  directly is by  $hhh$  production!

$\sigma_{hhh} \sim 100 \text{ fb} \sim \sigma_{hh}/2 @ \sqrt{s} = 40 \text{ TeV}$   
(effective theory) [Glover & v.d.Bij, NPB(309)282]  
× BRs is very tiny - certainly hopeless @ (SLHC)

Should be examined for VLHC!  
( $\sqrt{s} = 100, 200 \text{ TeV}$ )

Note - full loop calculation under study:  
[Thomas, Plehn, Zeppenfeld]

# Summary

- LHC Higgs review
  - No-Lose Theorems for (N)MSSM
  - detailed properties measurements  
(spin, CP, Yukawa+other couplings)
- Higgs pot. at hadron colliders
  - (s)LHC can study Higgs potential, complementarity with LC established
  - needs work: lep isol., fakes, ex. jets
  - SLHC: ok meas. for  $M_h < 150$
  - LHC: MSSM  $hh$  @ low  $\tan \beta$  unique
- $e^+e^-$  on  $hh$ 
  - very good precision for  $M_h < 140$
  - for  $e^+e^-$ , only CLIC can do  $M_h > 140$
- D5 operators:

probably not a concern,  
but interesting via rare decays
- $\lambda_{4h}$  out of reach everywhere

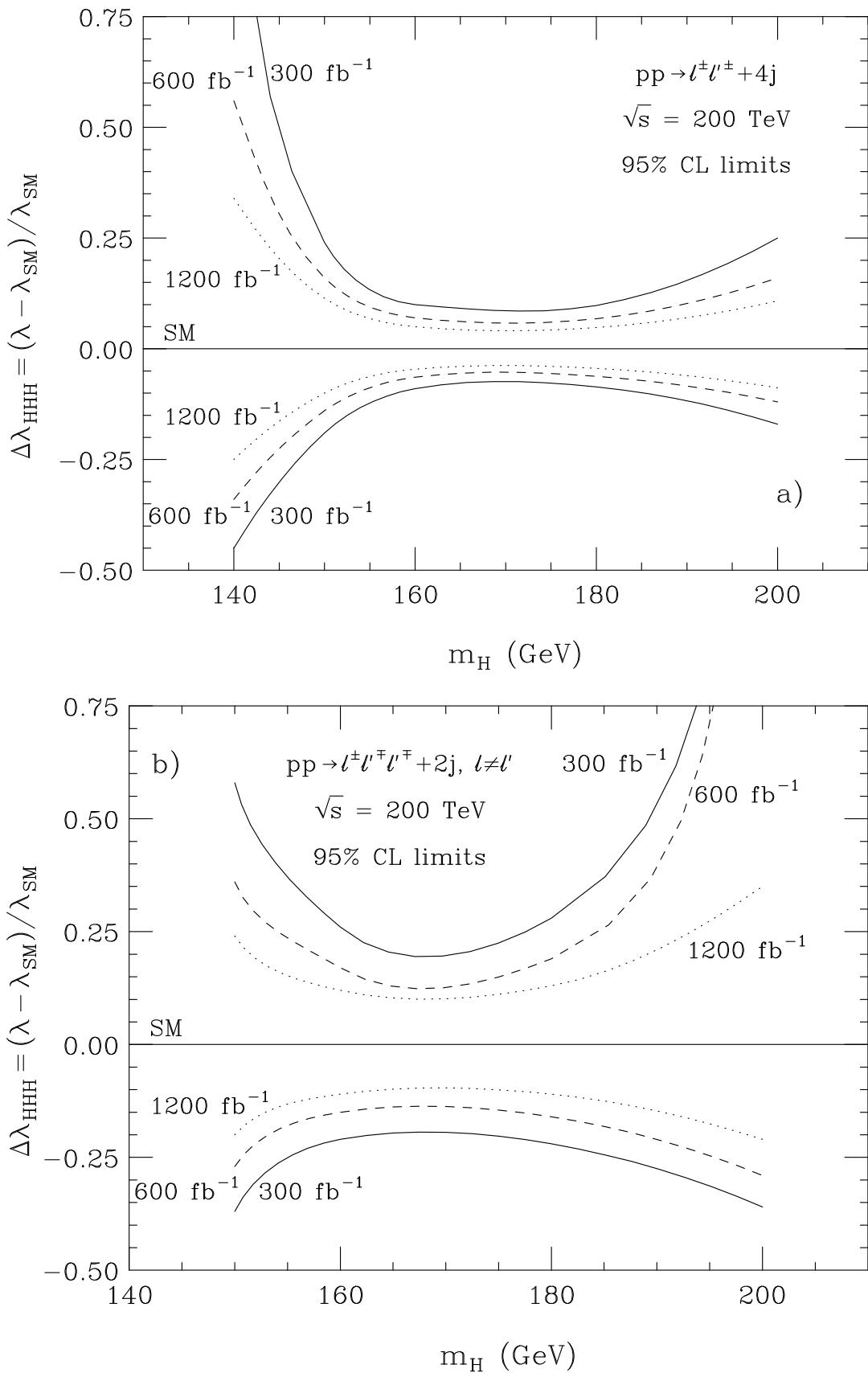
# LHC Higgs pheno recent progress

- multiple WBF channels w/ det. sim., neural nets
- $CP$  and  $g^{\mu\nu}$  coupling checks in  $hjj$  (WBF)  
[Plehn,DR,Zeppenfeld,PRL(88)051801],[Cranmer,Mellado,ATLAS]
- NLO rates for  $W/Z + jj, bb$   
[Campbell,Ellis,DR,hep-ph/0308195,PRDxxx]
- NLO rates for  $t\bar{t}h, b\bar{b}h$   
[Dawson et al., PRD(68)034022; Dittmaier et al., NPB(653)151,hep-ph/0309204]
- NNLO rates for  $gg, b\bar{b} \rightarrow h$   
[Harlander & Kilgore, PRL(88)201801,PRD(68)013001]
- top Yukawa from  $t\bar{t}h; h \rightarrow W^+W^-$   
[Maltoni,DR,Willenbrock,PRD(66)034022],[Leveque,ATLAS]
- global couplings analysis without assumptions  
[Dührssen, ATL-PHYS-2003-030]
- No-Lose Theorem for MSSM & NMSSM  
[Plehn,DR,Zeppenfeld,PLB(454)297; Ellwanger et al.,hep-ph/0305109],[ATLAS]
- NLO  $t\bar{b}H^-$  and understanding  $b$  partons  
[Plehn, PRD(67)014018; Boos & Plehn, hep-ph/0304034]
- NLO  $t\bar{t}j$  (soon) [Brandenburg,Dittmaier,Uwer,Weinzierl]
- Higgs self-coupling [Baur,Plehn,DR]

Unfortunately some disappointments as well...

- $H^\pm$  studies wrong - far too optimistic  
[T. Plehn & D. Zerwas, Les Houches 2003]
- $Wh; h \rightarrow b\bar{b}$  study too optimitstic (NLO  $Wbb$ )  
[Campbell,Ellis,DR,hep-ph/0308195,PRDxxx]
- $b$  Yukawa coupling extremely difficult!

# $hh \rightarrow 4W$ phenomenal @ VLHC



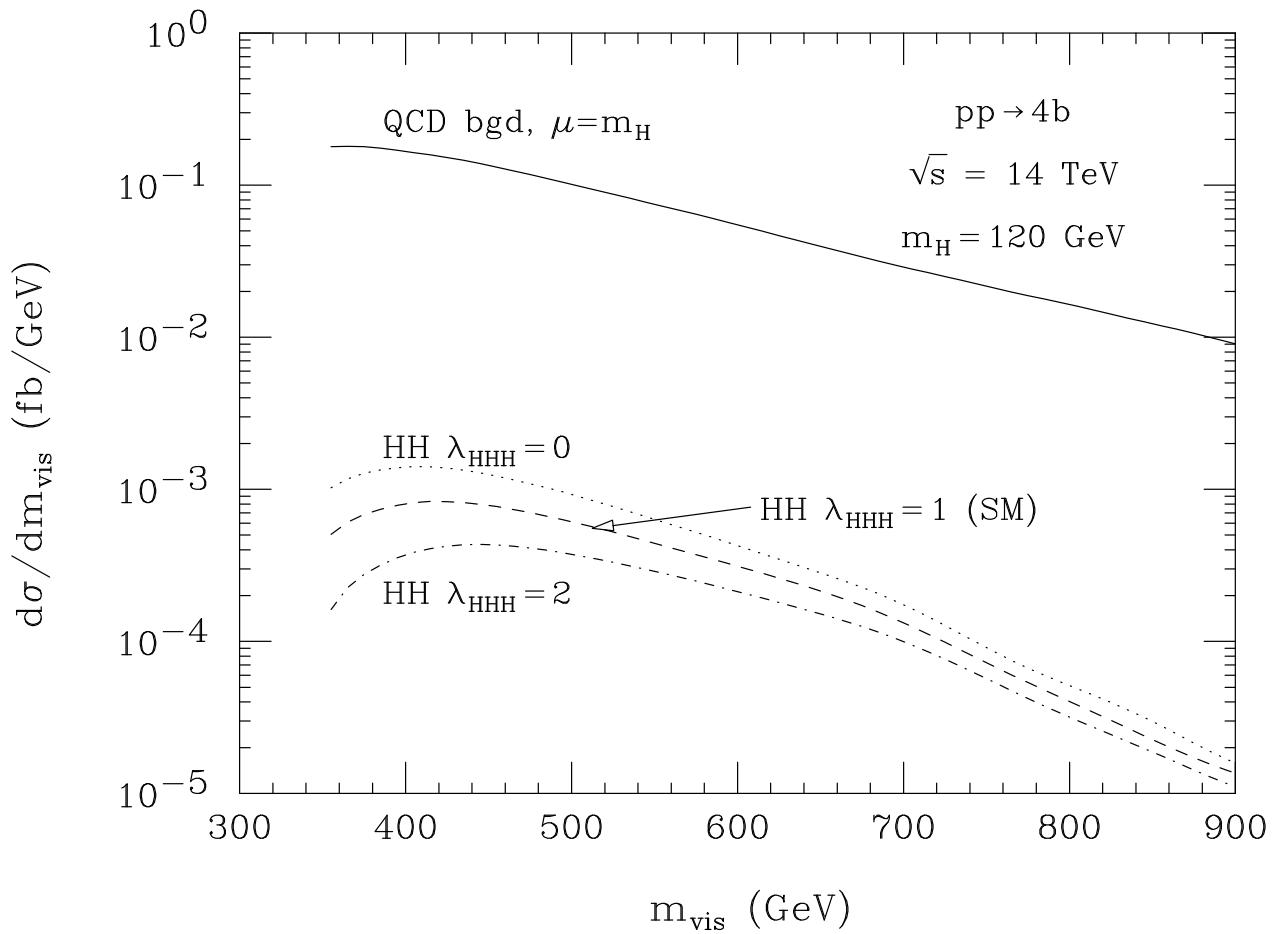
→ likely to be systematics dominated

# Lower $M_h$ region at the LHC

[Baur,Plehn,DR, PRD(68)033001), hep-ph/0310056]

Obvious channel is  $4b$  - largest BR

Unfortunately, QCD  $4b$  factor  $\sim 10^3$  larger

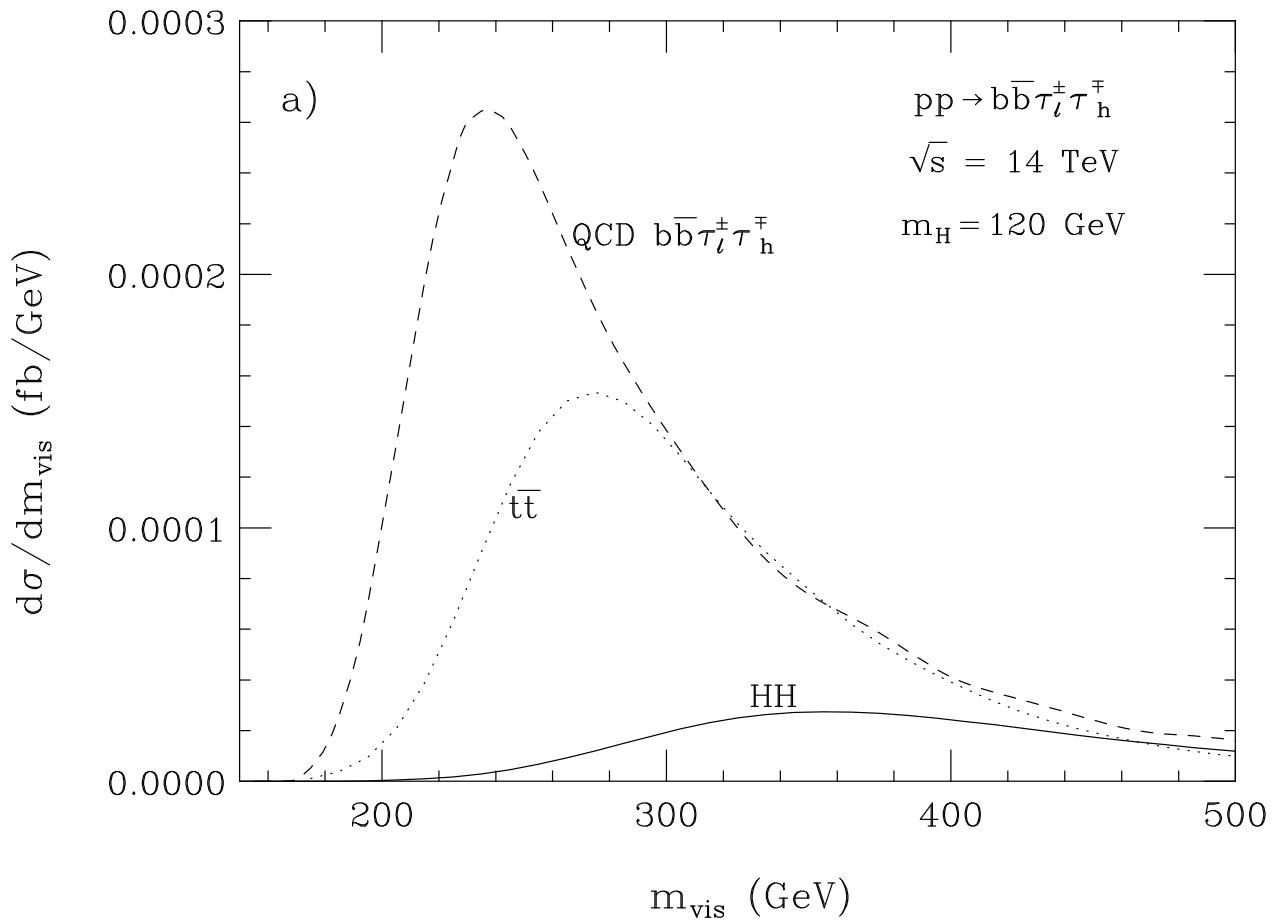


$M_h = 120 \text{ GeV}$ ,  $\epsilon_{ID}$  & QCD background:

lumi	$1\sigma$ upper	$1\sigma$ lower
LHC	+12	-9
SLHC	+ 7	-4

*Ok, try  $hh \rightarrow b\bar{b}\tau^+\tau^-$  instead*

Lose more bkg (EW v. QCD) than signal  
note: NLO results available for S & B!



No limits at LHC due to no events...

$$-1.6 < \Delta\lambda_{HHH} < 3.1 \quad (\text{SLHC})$$

$$-0.84 < \Delta\lambda_{HHH} < 0.96 \quad (\text{VLHC})$$

## What can a LC do?

$Zhh, hh\nu\bar{\nu}$  production channels

Numerous studies, focus on  $M_h < 140$  GeV

[Castanier *et al.*, hep-ex/0101028]

[Battaglia, Boos & Yao, hep-ph/0111276]

Not very thorough, have some problems...

Recently done with full simulation,  
for large  $M_h$  and various machines

[Battaglia & DeRoeck, post-LesHouches 2003]

→ see DeRoeck, WIN03